

GRAVITY'S SMOKING GUN?

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ABSTRACT

We present a new constraint on the biased galaxy formation picture. Gravitational instability theory predicts that the two-point mass density correlation function, $\xi(r)$, has an inflection point at the separation $r = r_o$, corresponding to the boundary between the linear and nonlinear regime of clustering, $\xi \simeq 1$. We show how this feature can be used to constrain the biasing parameter, $b^2 \equiv \xi_g(r)/\xi(r)$ on scales $r \simeq r_o$, where ξ_g is the galaxy-galaxy correlation function, allowed to differ from ξ . We apply our method to real data: the $\xi_g(r)$, estimated from the APM galaxy survey. Our results suggest that the APM galaxies trace the mass at separations $r \gtrsim 5 h^{-1} \text{Mpc}$, where h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{Mpc}^{-1}$. The present results agree with earlier studies, based on comparing higher order correlations in the APM with weakly nonlinear perturbation theory. Both approaches constrain the b factor to be within 20% of unity. If the existence of the feature we identified in the APM $\xi_g(r)$ – the inflection point near $\xi_g = 1$ – is confirmed by more accurate surveys, we may have discovered gravity's smoking gun: the long awaited “shoulder” in ξ , predicted by Gott and Rees 25 years ago.

Subject headings: Cosmology – large-scale structure of universe

1. INTRODUCTION

The concept that galaxies may not be fair tracers of the mass distribution was introduced in the early 1980s, in part in response to the observation that galaxies of different morphological types have different spatial distributions and that therefore they cannot all trace the mass (there are two excellent reviews on the subject: Strauss & Willick 1995 and Hamilton 1998). However, there was also another reason: to “satisfy the theoretical desire for a flat universe” (Davis et al. 1985, p.391). More precisely, biasing was introduced to reconcile the observations with the predictions of the Einstein-de Sitter cold dark matter (CDM) dominated model. At the time, it seemed that just a simple rescaling of the overall clustering amplitude by setting $\xi_g(r) = b^2 \xi(r)$, where $b \approx 2$ might do the job (Davis et al. 1985). However, very soon thereafter, it became clear that this is not enough: while the unbiased ($b = 1$) $\xi(r)$ had too large an amplitude at small r , the biased model did not have enough large-scale power to explain the observed bulk motions (Vittorio et al. 1987, Ostriker 1993). A similar conclusion could be drawn from comparison of the relative amplitude of clustering on large and small scales (eg Maddox et al 1990). The problem with the shape of $\xi(r)$ became explicit when measurements of $\xi_g(r)$ showed that the optically selected galaxies follow an almost perfect power law over nearly three orders of magnitude in separation. This result disagrees with N-body simulations. The standard ($\Omega_m = 1$) CDM model as well as its various modifications, including $\Omega_m < 1$ and

a possible non-zero cosmological constant, fail to match the observed power law (see Fig 11-12 in Gaztañaga 1995, Jenkins et al. 1998; most of these problems were already diagnosed by Davis et al. 1985). Two alternative ways out of this impasse were recently discussed by Rees (1999) and Peebles (1999). A possible response to the CDM crisis is to build a model where simple phenomena, like the power-law behavior of ξ_g are much more complicated than they seem. In particular, one can explore the possibility that the emergence of large scale structure is not driven by gravity alone but by “environmental cosmology” – a complex mixture of gravity, star formation and dissipative hydrodynamics (Rees 1999). A phenomenological formalism, appropriate for this approach was recently proposed Dekel & Lahav (1999). There are also some recent analytical models, based on halo profiles and halo-halo clustering (Seljak 2000, Scoccimarro et al 2001). An obvious alternative to environmental cosmology was recently discussed by Peebles (1999), who pointed out that “as Kuhn has taught us, complex interpretations of simple phenomena have been known to be precursors of paradigm shifts”. Instead, one can explore a simpler option, that galaxies trace the mass distribution, at least for local (low redshift), optically selected galaxies with a broad magnitude sampling. This approach rests on the idea that no matter how or where galaxies form, they must eventually fall into the dominant gravitational wells and therefore trace the underlying mass distribution (see Peebles 1980, hereafter LSS; Fry 1996).

The absence of biasing on large (weakly nonlinear) scales agrees well with other observational evidence. The measurements of the two-, three- and four-point connected moments of the density field in the APM catalog provide support for the hypothesis that galaxies trace the mass and also that the large-scale structure we observe today grew out of small-amplitude, Gaussian density fluctuations in an expanding, self-gravitating non-relativistic gas. Indeed, the theoretical predictions for the first few connected moments, based on this hypothesis (Juszkiewicz et al. 1993, Bernardeau 1994) are in good agreement with the APM measurements (Gaztañaga 1994, Gaztañaga & Frieman 1994, Frieman & Gaztañaga 1999, and references therein). The current precision of this higher order correlation test is 20% and expected to improve with future data. The absence of biasing is also suggested by the most recent measurements of the mean relative pairwise velocity of galaxies (Juszkiewicz et al. 2000).

In this *Letter* we propose a new test of the biasing hypothesis. Our test is based on the behavior of $\xi(r)$ at the $\xi = 1$ nonlinearity boundary. We describe our theoretical model in the next section. It is checked against N-body simulations in §3. It is then applied to the APM survey in §4. Finally, in §5 we discuss our results.

2. THE INFLECTION POINT

In the gravitational instability theory, newly forming mass clumps are generally expected to collapse before relaxing to virial equilibrium. If this were so, the relative mean velocity of particle pairs $|v_{12}(r)|$ would have to be larger than the Hubble velocity Hr to make $v_{12}(r) + Hr$ negative. As a consequence of the pair-conservation equation (LSS), the slope $d \ln \xi(r) / d \ln r \equiv -\gamma(r)$ must rapidly decrease with decreasing separation near the boundary of nonlinearity, i.e. when $r \lesssim r_o$. This effect was recognized long ago by Gott & Rees (1975). When the expected “shoulder” was not found in the observed galaxy-galaxy correlation function, Davis & Peebles (1977) introduced the so-called previrialization conjecture as a way of reducing the size of the jump in $\gamma(r)$ (the conjecture involves non-radial motions within the collapsing clump; see the discussion in LSS, §71 and Peebles 1993, pp. 535 - 541; see also Villumsen & Davis 1986; Lokas et al. 1996 and Scoccamarro & Frieman 1996). Later observational work showed a shoulder in ξ in several redshift and angular catalogs, which was also interpreted as evidence for the boundary between linear and nonlinear gravitational clustering (see the review by Guzzo 1997 and references therein).

Quarter a century later the precision of N-body simulations as well as the quality of the observational data have improved dramatically enough to justify a reexamination of the problem. The actual shape of the correlation function near $\xi = 1$ can be investigated with high resolution N-body simulations like those run by the Virgo Consortium (Jenkins et al. 1998). As shown in Juszkiewicz et al. (1999, hereafter JSD), in all four of the Virgo models (SCDM, Λ CDM, OCDM, τ CDM) the slope of $\xi(r)$ exhibits

a striking feature. Instead of a shoulder, or a simple discontinuity in $\gamma(r)$, however, $\xi(r)$ has an inflection point, $d^2 \xi(r) / dr^2 = 0$ which occurs at a uniquely defined separation $r = r_*$. At this separation, the logarithmic slope of ξ reaches a local maximum, $d \ln \xi / d \ln r = -\gamma_*$. In all models JSD investigated, the inflection point indeed appears near the transition $\xi = 1$, as expected by the earlier speculations, involving the “shoulder” in ξ . The separation r_* is almost identical with the scale of nonlinearity:

$$r_* \approx r_o, \quad \xi(r_o) \equiv 1. \quad (1)$$

More precisely, a comparison of Figure 1 in JSD with Figure 8 in Jenkins et al. (1998) gives

$$|r_o - r_*| < 0.1 r_o \quad (2)$$

for all four considered models. Moreover, for all models, studied by JSD, the $-\gamma$ vs. r dependence can be described as an S-shaped curve, with a maximum at $r = r_* \approx r_o$, and a minimum at a smaller separation. The depth of the minimum in $-\gamma(r)$ increases with increasing normalization parameter, σ_8 – the final linear rms mass density contrast, measured in spheres of a radius of $8 h^{-1} \text{Mpc}$ (see Fig.8 in JSD). If the relation (1) is indeed a general property of gravitational clustering, it can be used as a test of biasing as follows. Suppose the biasing factor is significantly greater than unity: $b \gg 1$. Then $\xi_g \gg \xi$ and the relation (1) will break down. For power-law galaxy correlation function, $\xi_g(r) = (r_{og}/r)^\gamma = b^2 \xi(r)$, and instead of equation (1) we will have $r_* \approx r_{og} b^{-2/\gamma}$. Since the observed slope is $\gamma \approx 1.8$, for $b = 2$, the shoulder in the correlation function should appear at a separation smaller than a half of the r_{og} parameter! The technique we propose is unable to constrain more baroque biasing models with a large number of free parameters. However, the predictive power of such models is questionable and one may ask: are they falsifiable at all?

3. APM-LIKE N-BODY SIMULATIONS

In this section, we compare the JSD analytic and N-body results with a different set of P³M simulations. Instead of the family of CDM models, considered by JSD, we use APM-like initial conditions, which have Gaussian initial conditions with an initial power spectrum designed to evolve into a final spectrum, matching the APM measurements, under the additional assumption of no bias and $\Omega_m = 1$. We use simulations with identical APM-like spectrum, with $\Lambda = 0$ and two different values of the density parameter: $\Omega_m = 1$ and 0.3. The box size is $600 h^{-1} \text{Mpc}$ (or $300 h^{-1} \text{Mpc}$) with 200^3 (or 100^3) dark matter particles with $\sigma_8 = 0.85$ (for more details see Baugh & Gaztañaga 1996).

The evolved, nonlinear correlation functions, measured from simulations are shown in Figure 1 (top left panel). The full squares correspond to the $\Omega_m = 1$ model, while the open squares represent $\Omega_m = 0.3$. For comparison, we show the linear correlation function (dashed line). Nonlinear effects are more pronounced in the low density model.

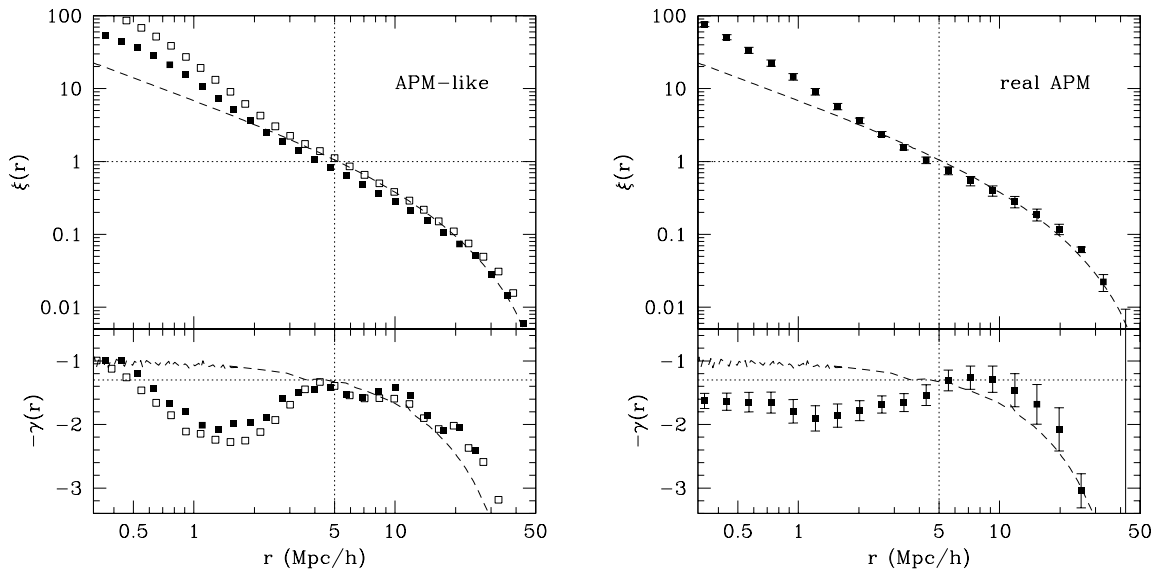


FIG. 1.— *Top left panel:* linear $\xi(r)$ (dashed line) and the measured nonlinear $\xi(r)$, obtained from the APM-like simulations with $\Omega_m = 0.3$ (open squares) and $\Omega_m = 1.0$ (full squares). *Bottom left panel:* Corresponding logarithmic slope, $-\gamma(r) = d \ln \xi / d \ln r$ for each of the three curves from the top panel. The right panels show similar results for the spatial $\xi(r)$ estimated for APM galaxies (symbols with errorbars), compared to the same linear theory APM-like model (dashed line). The vertical dotted lines shows the scale r_o , defined by the condition $\xi(r_o) = 1$ (top) and the scale r_* , at which the nonlinear $\gamma(r)$ curve crosses the linear one (bottom).

Note however, that although the correlation functions differ significantly in amplitude at separations $r < 2h^{-1}\text{Mpc}$, their slopes $\gamma(r)$ are almost indistinguishable.

The particle resolution (the Nyquist wavelength $\propto N^{-1/3}$) of the simulations used here is significantly lower than the resolution of Virgo simulations, and the noise in the measured $\xi(r)$ is further amplified by differentiating over r . As a result, determining the position of the inflection point r_* directly from the $\gamma(r)$ curve alone is more difficult. A noise-resistant, alternative definition of r_* , suggested by JSD is to identify r_* with the separation at which the linear $\gamma(r)$, derived from initial conditions, crosses the nonlinear $\gamma(r)$ curve, measured from the simulations. This approach is indeed effective for our APM-like simulation (see Fig.1), but it can not be applied to the true APM data since we know only the nonlinear $\gamma(r)$. The observed $-\gamma(r)$ curve does resemble the S-shaped $-\gamma(r)$ from the VIRGO simulations; the main difference is that the peak as well as the trough are broad and fuzzy rather than narrow and sharp as in the simulations. To deal with this problem, we used the following prescription. For a discrete set of measurements $r_i, \gamma(r_i)$, $i = 1, 2, \dots$ starting with some separation r_1 rightward of the peak, and moving to smaller separations, we compare consecutive values of $-\gamma(r_i)$ and $-\gamma(r_{i+1})$. We then identify r_* with the largest r_i , for which $-\gamma(r_i)$ drops below its maximum value for the next few points (this is to avoid picking up local maxima due to fluctuations, see Fig.1). Obviously, the above prescription would also pick r_* in high resolution simulations. When applied to the APM-like simulations, this method gives $r_* \simeq 4 - 5 h^{-1} \text{ Mpc}$. The same simulations also give $r_o \simeq 5 h^{-1} \text{ Mpc}$, in excellent agreement with equation (2),

which we will consider as a measure of a systematic error, introduced by the theoretical model we use. From these simulations we conclude that equality between r_* and r_o can probably be considered as a generic outcome of gravitational dynamical evolution in a model where galaxies trace the mass and the initial slope, $d \ln \xi / d \ln r$, is a smooth decreasing function of the separation r (as expected in hierarchical clustering models, see e.g. LSS).

4. COMPARISON WITH OBSERVATIONS

The measurements of $\xi_g(r)$, and $\gamma(r) \equiv -d \ln \xi_g / d \ln r$, obtained from the angular correlations of galaxy pairs in the APM catalog (Baugh 1996), are plotted in Figure 1. Errorbars correspond to the dispersion in $\gamma(r)$ from 4 APM strips of about 30×60 degrees each, eg $200 \times 400 h^{-1} \text{ Mpc}$ at the mean depth of the APM. At scales of $r \simeq 5 h^{-1} \text{ Mpc} \ll 200 h^{-1} \text{ Mpc}$ most of the covariance between consecutive bins in ξ_g is due to large scale density fluctuations that shift the mean density between strips. This introduces covariance in the amplitude of $\xi_g(r)$ (the whole ξ_g curve is shifted vertically from strip to strip, see eg Fig.2 in Baugh 1996), but does not affect much its shape $\gamma(r)$. Thus, we consider our errors in $\gamma(r)$ as independent. The top left panel shows the two-point function (points with error bars), and the linear theory curve, described in §3 (dashed line). The intersection of the two perpendicular dotted lines marks the point $(\xi_g, r) = (1, r_{og})$. The bottom panel of Figure 1 shows the APM $\gamma(r)$ as a function of the pair separation r . Note the remarkable similarity between the empirical data and the characteristic peak in the $-\gamma(r)$ found in the simulations (compare the left and right bottom panels in Fig.1; see also Fig.1 in JSD). The inter-

section of the two mutually perpendicular, dotted lines in the bottom panel of Figure 1 marks the result of applying our prescription for estimating r_* to the APM data. The slope $-\gamma$ drops down from its maximum value at the separation $r \simeq 5 h^{-1}\text{Mpc}$, and to first approximation this scale could be identified with r_* . Taking into account the error bars in Figure 1 we obtain $r_* \simeq (5.5 \pm 1.5) h^{-1}\text{Mpc}$, $r_{og} \simeq (4.5 \pm 0.5) h^{-1}\text{Mpc}$ and $\gamma_* \simeq -1.4$. From these measurements one can estimate b in the linear bias model

$$b^2 = (r_{og}/r_*)^{\gamma_*}. \quad (3)$$

This expression for b^2 is also exactly valid for a non-linear scale-dependent bias at $b(r_o)$ as far as $r_* \simeq r_o$: $b^2(r_o) \equiv \xi_g(r_o)/\xi(r_o) \equiv (r_{og}/r_o)^{\gamma(r_o)} = (r_{og}/r_*)^{\gamma_*}$. This is true even if the slopes of the galaxy and matter correlations are different at $r = r_o$. We find

$$b(r_o) \simeq 1.15 \pm 0.23 (\pm 0.11) \quad (4)$$

at one-sigma level in the errors. The error in parenthesis corresponds to the systematic uncertainty in Eq.2.

5. DISCUSSION

Recently, Hamilton and Tegmark (2000) found no evidence of an inflection at the linear-nonlinear transition scale in ξ_g , estimated from the PSCz survey. The origin of this difference with our APM results is not clear, since a recent study of the three-point correlations in the PSCz catalog (Feldman et al. 2001) leaves little room for biasing, providing constraints on b similar to those obtained here and to those obtained earlier from the measurements of three-point correlations in the APM catalog. If the APM inflection as well as its absence in the PSCz are both real

phenomena, it then means that APM galaxies are less biased than PSCz (IRAS) galaxies. Apart from constraining the linear bias, Feldman et al. have also measured a small but statistically significant second-order biasing parameter, consistent with the observation that infrared-selected (IRAS) galaxies avoid high density cores of clusters. We plan a systematic study of this effect in near future.

We are impressed how well the shape of $\gamma(r)$ in the APM observations resembles gravity's "shoulder". This feature is a robust result from the APM catalogue and can be seen directly in the angular 2-point function and in the recovered shape of the power spectrum (Baugh & Efstathiou 1993). Numerical simulations (Gaztañaga & Baugh 1996) show that this is not an artifact of the de-projection. It is difficult to imagine how such an agreement could happen by a mere coincidence, which would have to be the case if ξ_g is unrelated to ξ . Our results are by no means final, they are also less rigorous than one could wish because we are limited by the accuracy of the present observational data. New generation of catalogs promise an improvement on this front in the near future (for an excellent collection of reports on the state of the art in this field, see Colombi et al. 1998).

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